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# In-Line Charaterization of HPSI SiC Wafers Using High Resolution Surface Photovoltage Spectroscopy (HR-SPS)

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**Abstract.** High purity semi-insulating (HPSI) 4H-SiC wafers from different vendors have been studied by surface photovoltage spectroscopy (SPV). It is demonstrated that the surface photovoltage signal height can be used to discriminate between non-compensated and compensated material, and that the SPV signal is also proportional to the bulk resistivity, at least for non-compensated 4H-SiC material.

## Introduction

Silicon Carbide (SiC) is a key semiconductor substrate for advanced power and RF electronics, epitaxial graphene on SiC for high sensitivity gas and magnetic sensing devices being very exciting examples on possible future sensory devices based on SiC. RF operation require an insulating or at least a semi-insulating base substrate on top of which the active device layers are grown. The basic wafer for RF electronics/sensory devices consists of a high resistivity, semi-insulating 4H-SiC wafer with a thin epitaxial SiC, GaN or graphene layer on top (typically < 1 µm in thickness). On such epitaxial wafers, RF FETs or for instance Hall magnetic sensors are being processed. Hall magnetic sensors with minimum detectable fields < 0.1 µT√Hz @ 5 µA drive current has been demonstrated using graphene epitaxial layers on semi-insulating 4H-SiC wafers [1], opening the way for many interesting applications such as accurate navigation and position tracking [2] using ultra-compact, low power sensor devices.

Growing large diameter, semi-insulating SiC material has proven to be a difficult matter, because both the axial and radial variations in the grown material are large. Therefore, a high degree of binning is taking place when producing electronic grade and epi-grade wafers – binning the raw wafers or the processed wafers into categories of different performance. Between the different manufacturers of semi-insulating SiC wafers there is large variation in degree of compensation (the levels of B, Al and N can vary over 2-3 orders of magnitude. This paper presents a new analysis tool that can be used on large area wafers and which provide fast and accurate information about the state of the semi-insulating SiC semiconductor material.

The new analysis tool uses the surface photovoltage measurement technology to extract information on the state of the SiC semiconductor material by using a multiple, discrete wavelength approach that excite photogenerated carriers with different energies in the SiC semiconductor. In this paper, results obtained using the Freiberg Instruments GmbH non-contact high-resolution surface photovoltage spectroscopy (HR-SPS) tool on SiC high purity, semi-insulating (HPSI) semiconductor materials are presented. We show that the non-contact tool can be used to discriminate between HPSI SiC wafers with respect to defects and degree of compensation.

## Experimental

The HR-SPS tool (see Fig. 1 below) is a desktop tool with automatic sample detection, R-Phi mapping table and sample height Z-axis control. In this series of experiments, each sample is mapped with a spatial resolution of 0.25 mm and a distance between the sample surface and the SPV signal pick-up electrode of 0.3 mm. The signal pick-up electrode is 2 mm in diameter and with a hole in the middle that allow light to be guided to the sample. The light sources are chosen according to the material to be investigated. In case of 4H-SiC the recommendation is to use light sources in a range from 320 nm and up to 500 nm. 4H-SiC has an indirect bandgap at 3.26 eV (equivalent wavelength ~ 380 nm) and a mix of light sources with energies above and below the bandgap energy is optimal to study defects and doping distribution effects. The surface photovoltage signal height, which is a direct measure of the density and separation of the photogenerated carriers, is measured electronically using a capacitive readout circuit with low parasitic components and a high signal-to-noise ratio. The measurements are all done by flooding and saturating the semi-insulating 4H-SiC semiconductor with photogenerated carriers and a measurement of the maximum surface photovoltage signal height achieved during flooding. After turning off the light source(s), the photogenerated carriers, i.e. the surface photovoltage signal, undergoes a relaxation process that can last up to hundreds of milliseconds. Valuable information about the material can be obtained by monitoring the time-dependent surface photovoltage signal after having turned off the light source(s), but this is not the topic of this article.

4 HPSI on-axis 4H-SiC wafer pieces (20 x 20 $mm^2$ in size) from 4 different vendors have been analyzed using the HR-SPS technology. The information of the 4 pieces of material were scarce; 3 of them were PVT grown samples and one was CVD grown. One PVT sample was confirmed to be non-compensated and with bulk resistivity > 1E9 Ω-cm (1E9i), another PVT sample was confirmed to have a bulk resistivity > 1E8 Ω-cm (1E8ic), but with no direct information on the doping levels. Two samples had a very high confirmed bulk resistivity > 1E11 Ω-cm – one was a PVT-piece, the other a CVD-piece (1E11c & 1E11CVD, respectively), the indices i and c are used for intrinsic (non-compensated) an c (compensated), respectively. The SPV signal height was measured for all wafer pieces at the Si terminated side of the wafer and at 3 different wavelengths; 355 nm, 375 nm and 450 nm. It is known that the light absorption coefficient is very high at 450 nm, when a lot of nitrogen-vacancies are present in the bulk of the 4H-SiC material [3]. A high SPV signal is thus an indication of nitrogen in the bulk. Light at 355 nm has a high enough energy to generate holes and electrons across the bandgap and if the separation of carriers is driven by the surface build-in field, high SPV signals are expected at 355 nm. The excitation at 375 nm is interesting, because it is expected that non-compensated and compensated 4H-SiC have significantly different properties close to the bandgap energy edge (excitonic effects as an example). In the following the results for the 3 PVT grown pieces will be presented and discussed in detail. The results for CVD grown piece will be used together with the other 3 pieces for building a response model based on degree of compensation.

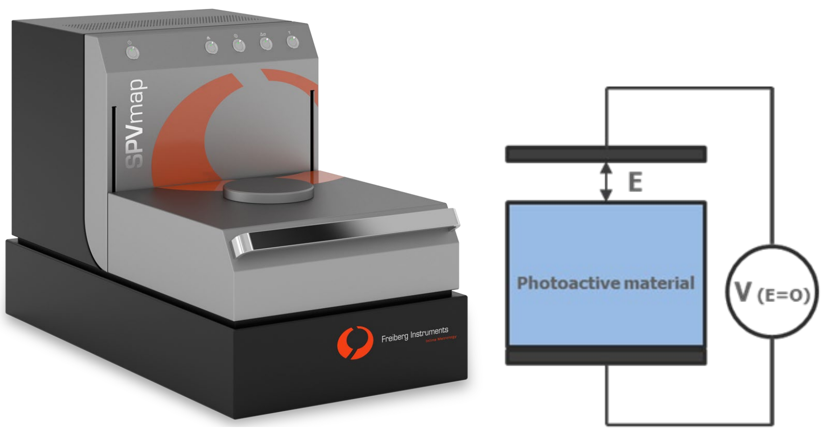


**Fig. 1.** Freiberg Instruments GmbH HR-SPS mapping tool and principle of operation

## Results

In Fig. 2 maps and statistics of surface photovoltage measurements of SiC wafer pieces @ 355 nm for the 3 different PVT samples are shown. Two samples are non-compensated, but with no information about how the point defects responsible for the high resistivity have been introduced.

The third sample is compensated. Between the two non-compensated HPSI 4H-SiC samples, there is a difference in the SPV signal height, which can be either due to the difference in bulk resistivity or due to a difference in point defect concentration. The signal responses are identical with a high positive peak and a fast relaxation time The SPV signal height for the compensated sample is very low in spite of the high bulk resistivity, but it is not surprising that the SPV signal is low, because of the high density of dopants. Likely, very fast relaxation processes are dominating the surface dynamics.

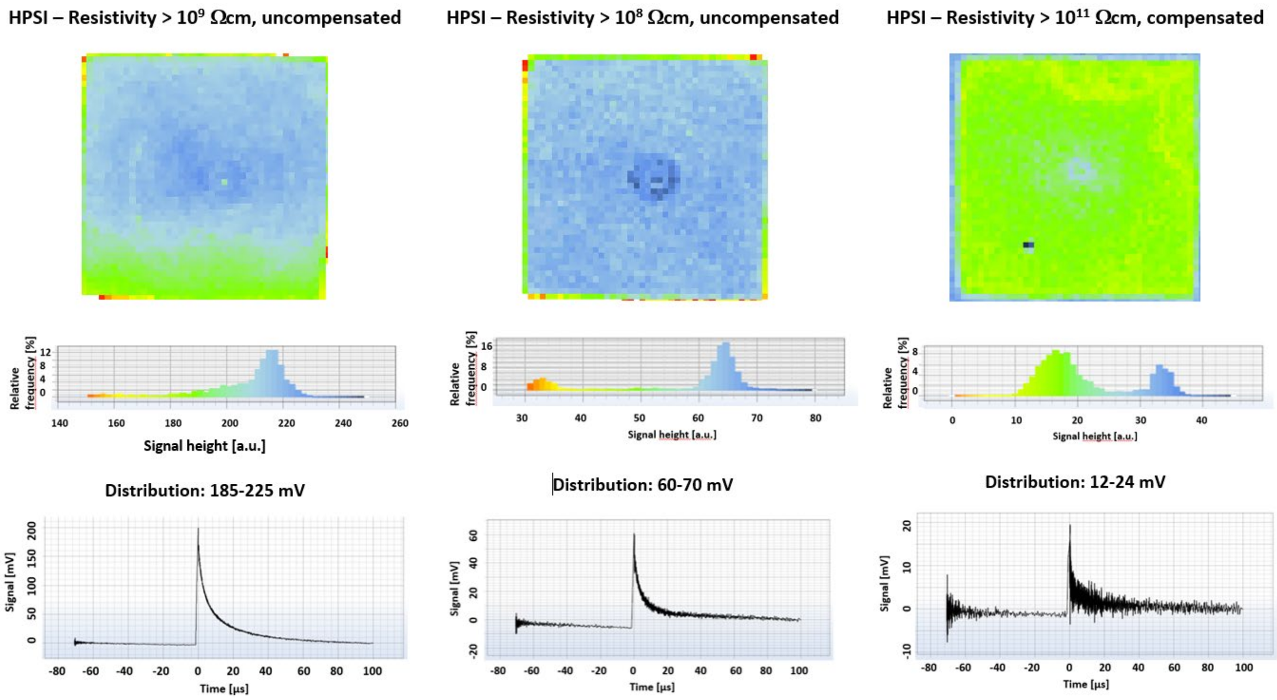


**Fig. 2.** SPV signal height mapping @ 355 nm for 3 wafer samples, each 20 x 20 mm$^2$ in size.

In Fig. 3 maps and statistics of surface photovoltage measurements of SiC wafer pieces @ 450 nm for the same 3 samples are shown. It is known that nitrogen dopants in SiC absorbs light around 460 nm and SPV can therefore be used to determine the level of the nitrogen concentration [3]. One of the non-compensated samples, as well as the compensated sample show high values of the SPV signal and both have therefore relatively high levels of nitrogen. The non-compensated sample (1E9i) has a very low SPV signal at 450 nm, suggesting low levels of nitrogen in the bulk. A high level of nitrogen is expected in the compensated sample and may also explain the lower SPV signal height for one of the non-compensated samples at 355 nm.

In Fig. 4 maps and statistics of surface photovoltage measurements of SiC wafer pieces @ 375 nm for the same 3 samples are shown. It is known that the optical absorption of light starts to decrease around 365 nm and that the lights penetrates ~ 300 µm into the 4H-SiC material at 375 nm. The compensated sample has a very high SPV signal and the relaxation process is dominated by one process only (Fig. 4). For the two other samples (non-compensated) backside effects (probe ID scratching) are clearly seen in the map, suggesting that the light has penetrated to the back side of the sample. One possible explanation for the increased absorption for the compensated sample, is bandgap effects due to the high concentrations of dopants.

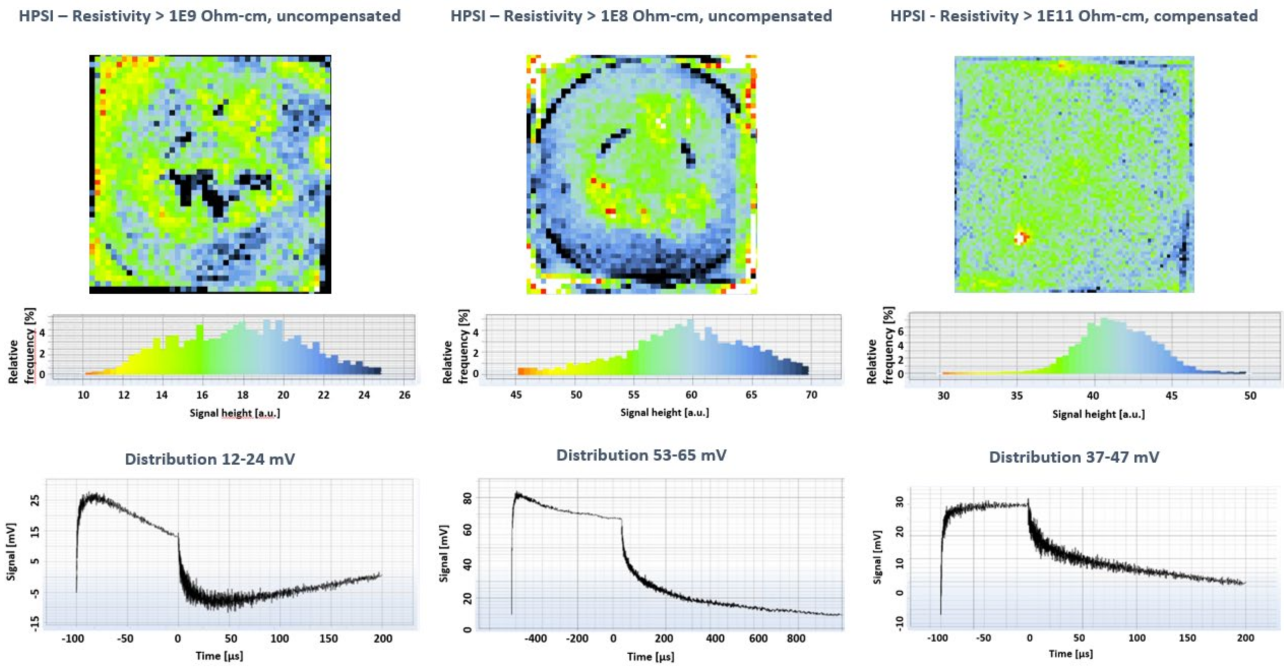


**Fig. 3.** SPV signal height mapping @ 450 nm for the same 3 wafer samples as in Fig. 2.

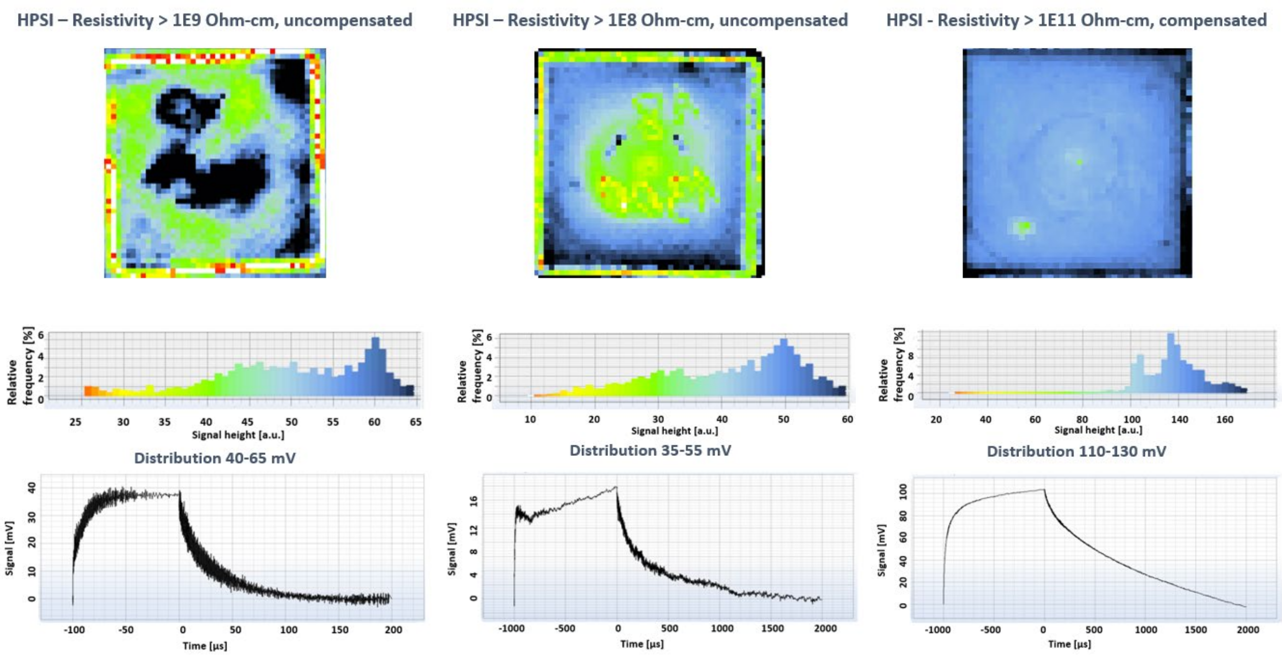


**Fig. 4.** SPV signal height mapping @ 375 nm for the same 3 wafer samples as in Fig. 2

## Discussion

The HR-SPS technology can be used to investigate HPSI 4H-SiC wafers before and after processing of the wafers and their degree of compensation. Each wafer has a “watermark” which can be read using the HR-SPS technology using a combination of different wavelength (or energy) excitations to generate free photocarriers. Some of these separate in space and give rise to a high SPV signal, but others recombine very fast because of deep levels that are absorbing one of the photogenerated carrier types (electrons or holes), resulting in a very low SPV signal. A full map takes about 30 minutes per 200 mm wafer (with a spatial resolution of 1mm), but a 49-star point map takes only 2 minutes.

In Fig. 5 is shown the "watermark" of each of the 4 wafer pieces. The PVT 1e9i non-compensated sample seem to be dominated by two processes, one for energies above the bandgap energy and another for energies below the bandgap energy. The PVT 1e8ic sample has a somewhat different "watermark" with relatively low SPV values for all three wavelengths. The low SPV value at 355 nm can be because of the lower bulk resistivity in comparison with the 1e9i sample. The slightly higher SPV value for the 1e8ic sample compared to the 1e9i at 450 nm indicates the presence of more nitrogen dopant in the 1e8ic, which is in accordance with the SPV values at 355 nm.

The two compensated samples (1E11c and 1E11CVD) have a very different behavior ("watermark" to the non-compensated samples, but the two compensated samples behave overall the same. Both of them seem to have relatively low concentrations of nitrogen in the bulk material, but the behavior at 375 nm is interesting.

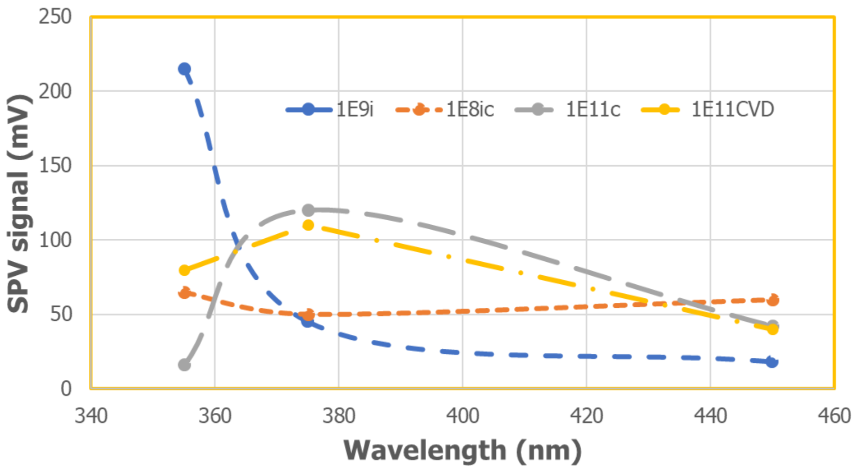


**Fig. 5.** Mean SPV signal as a function of the wavelength. The lines between the discrete wavelength measurement points only serve as a guide to the eye.

## Conclusions

The electrical properties of semi-insulating (SI) SiC are different depending on how the high bulk resistivities are achieved, and this difference between wafers can lead to a large spread in parameters for advanced electronics and sensory devices based on processed SI 4H-SiC wafers. The SPV approach, combined with flooding of photocarriers, as it is implemented in the HR-SPS tool from Freiberg Instruments GmbH, can be used to make quantitatively based decisions on the goodness of both the raw and the processed material and thereby be used to improve performance and/or yield of devices based on SI 4H-SiC.

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